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Enhancement of Power Quality by Multi – Connected Distributed Power Flow Controller (MC-DPFC)

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ABSTRACT: This paper presents a new component within the Flexible AC Transmission System (FACTS) family, called Distributed Power Flow Controller (DPFC) capable of simultaneous compensation for the voltage and current in multi bus system. DPFC is derived from the UPFC with an eliminated common DC link. In this configuration one shunt voltage source converter and two or more series voltage source converters exist. The system can be applied to adjacent feeders to compensate for supply-voltage and load current imperfections on the main feeder. The active power exchange between the shunt and series converters, which is through the common dc link in the UPFC, is now through the transmission lines at the third-harmonic frequency. The DPFC can be designed with multiple single phase series converters (DFACTS) and one three phase shunt converter. The reliability of the DPFC system is further improved by the use of multiple single phase series converters with the adapted control schemes. The DPFC having much control capability like UPFC, however at much reduced cost and an improved reliability. The DPFC has the same control capability as the UPFC, which comprises the adjustment of the line impedance, the transmission angle, and the bus voltage. The principle and analysis of the DPFC are presented. The case study contains a DPFC sited in a single-machine infinite bus power system including two parallel transmission lines, which simulated in MATLAB/ Simulink and the results validate the DPFC ability to improve the power quality

KEYWORDS

Power Quality, FACTS, Distributed Power Flow Controller (DPFC), UPFC.

I. INTRODUCTION

Recent developments in the electric utility industry are encouraging the entry of power quality issue [1]. Extending from the generation units to the utility customers, power quality is a measure of how the elements affect the system as a whole [2]. From customer point of view, the power quality issue is concerned about current, voltage or frequency deviation which results in power failure [3]. To solve the power quality problem in such a situation, the power electronic devices such as flexible alternating-current transmission system (FACTS) and custom power devices (DVR) which are used in transmission and distribution control, respectively, should be developed [4], [5], [6]. The impact of transient parameters in majority of transmission lines problems such as sag (voltage dip), swell (over voltage) and interruption, are also considerable [1]. To mitigate the mentioned power quality problems, the utilization of FACTS devices such as power flow controller (UPFC) and synchronous static compensator (STAT-COM) can be helpful [7] , [8]. In [9], the distributed power flow controller (DPFC) is presented which has a similar configuration to UPFC structure. As shown in Fig. 1, the DPFC is composed of a single shunt converter and multiple independent series converters which is used to balance the line parameters, such as line impedance, transmission angle and bus voltage magnitude [9], [10]. To detect the voltage sags and determine the three single-phase reference voltages of DPFC, the SRF method is also proposed as a detection and determination method. The work in this paper is organized as follows: introduction to DPFC and operation principle is debated in Section II. In Section III, the control strategy of DPFC. The impact of DPFC in power quality enhancement is investigated in Section IV. Finally, the case study and its simulation results are analyzed in the last part of this work.

II. INTRODUCTION TO DPFC

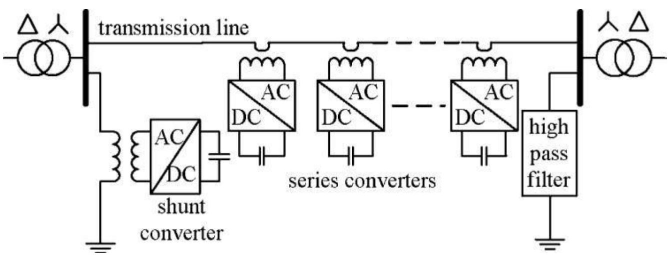

Fig 1: DPFC configuration.

The DPFC consists of one shunt and several series-connected converters. The shunt converter is similar as a STATCOM, while the series converter employs the D-FACTS concept, which is to use multiple single-phase converters instead of one large rated converter. Each converter within the DPFC is independent and has its own dc capacitor to provide the required dc voltage. The configuration of the DPFC is shown in Fig 1 , besides the key components, namely the shunt and series converters, the DPFC also requires a high-pass filter that is shunt connected at the other side of the transmission line, and two Y–Δ transformers at each side of the line. The unique control capability of the UPFC is given by the back-to-back connection between the shunt and series converters, which allows the active power to exchange freely. To ensure that the DPFC have the same control capability as the UPFC, a method that allows the exchange of active power between converters with eliminated dc link is the prerequisite. Within the DPFC, there is a common connection between the ac terminals of the shunt and the series converters, which is the transmission line. Therefore, it is possible to exchange the active power through the ac terminals of the converters. The method is based on the power theory of non sinusoidal components.

According to the Fourier analysis, a non sinusoidal voltage and current can be expressed by the sum of sinusoidal functions in different frequencies with different amplitudes. The active power resulting from this non sinusoidal voltage and current is defined as the mean value of the product of voltage and current. Since the integrals of all the cross product of terms with different frequencies are zero, the active power can be expressed by

$$P = \sum_{i=1}^{\infty} V_i I_i \cos \emptyset_i$$

By applying this method to the DPFC, the shunt converter can absorb active power from the grid at the fundamental frequency and inject the current back into the grid at a harmonic frequency. This harmonic current will flow through the transmission line. According to the amount of required active power at the fundamental frequency, the DPFC series converters generate a voltage at the harmonic frequency, thereby absorbing the active power from harmonic components. Assuming a lossless converter, the active power generated at fundamental frequency is equal to the power absorbed from the harmonic frequency. For a better understanding, Fig. 3 indicates how the active power exchanges between the shunt and the series converters in the DPFC system. The high-pass filter within the DPFC blocks the fundament frequency components and allows the harmonic components to pass, thereby providing a return path for the harmonic components. The shunt and series converters, the high-pass filter, and the ground form the closed loop for the harmonic current. Due to the unique characters of third-harmonic frequency components, the third harmonic is selected to exchange the active power in the

DPFC. In a three-phase system, the third harmonic in each phase is identical, which is referred to as "zero-sequence." The zero sequence harmonic can be naturally blocked by Y–Δ transformers, which are widely used in power system to change voltage level. Therefore, there is no extra filter required to prevent the harmonic leakage to the rest of the network. In addition, by using the third harmonic, the costly high-pass filter, as shown in Fig. 3, can be replaced by a cable that is connected between the neutral point of the Y–Δ transformer on the right side in Fig. 2 and the ground. Because the Δ winding appears open circuit to the third-harmonic current, all harmonic current will flow through the Y-winding and concentrate to the grounding cable, as shown in Fig. 3. Therefore, the large-size high-pass filter is eliminated.

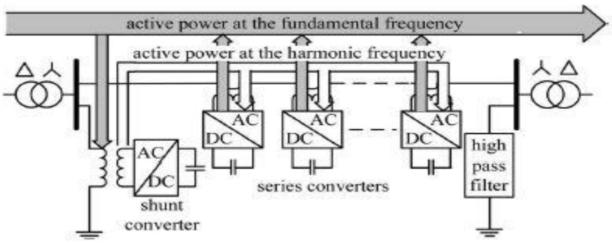

Fig. 2. Active power exchange between DPFC converters

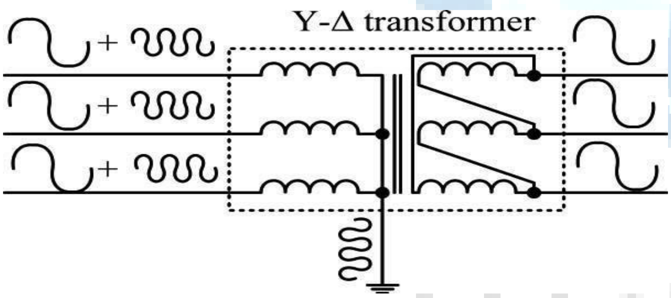

Fig 3 : Utilize Grounded Y–Δ transformer to provide the path for the zero-sequence third harmonic

Another advantage of using third harmonic to exchange active power is that the way of grounding of Y–Δ transformers can be used to route the harmonic current in a meshed network. If the branch requires the harmonic current to flow through, the neutral point of the Y–Δ transformer at the other side in that branch will be grounded and *vice versa*. Fig. 4 demonstrates a simple example of routing the harmonic current by using a grounding Y–Δ transformer. Because the transformer of the line without the series converter is floating, it is open circuit for third-harmonic components. Therefore, no third-harmonic current will flow through this line.

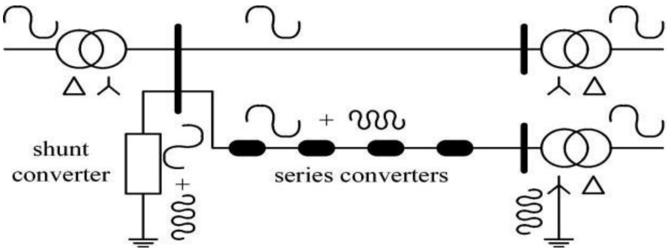

Fig.4 Route the harmonic current by using the grounding status of the Y–Δ transformer

Theoretically, the third-, sixth-, and ninth-harmonic frequencies are all zero-sequence, and all can be used to exchange active power in the DPFC. As it is well known, the capacity of a transmission line to deliver power depends on its impedance. Since the transmission-line impedance is inductive and proportional to the frequency, high transmission frequencies will cause high impedance. Consequently, the zero-sequence harmonic with the lowest frequency—third harmonic is selected.

III. DPFC CONTROLLER

The DPFC has three control strategies: central controller, series control, and shunt control, as shown in Fig. 5.

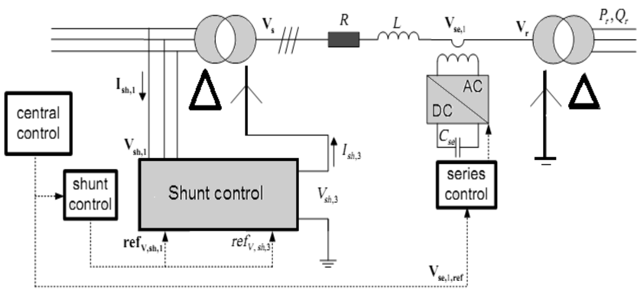

Fig. 5. DPFC control structure.

A. *Central Control*

This controller manages all the series and shunt controllers and sends reference signals to both of them.

B. *Series Control*

Each single-phase converter has its own series control through the line. This controller inputs are series capacitor voltages, line current and series voltage reference in dq-frame. Any series controller has one low-pass and one 3rd-pass filter to create fundamental and third harmonic current respectively. Two single-phase phase lock loop (PLL) are used to take frequency and phase information from network [11]. The simulated diagram of series controller is shown in Fig. 6

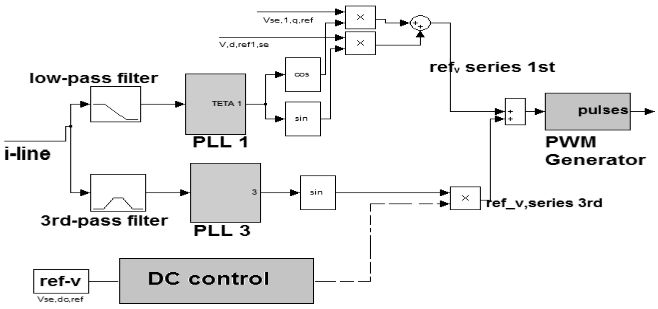

Fig. 6. The series control structure.

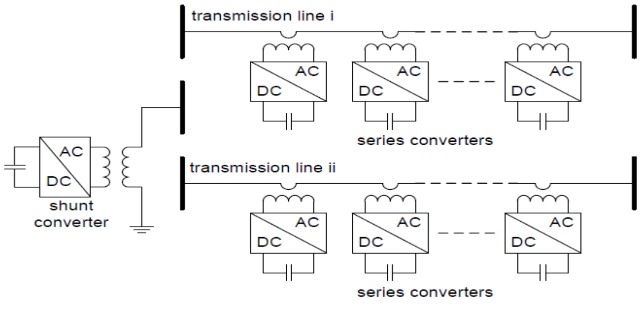

Figure 8 MC-DPFC configuration

C. *Shunt Control*

The shunt converter includes a three-phase converter which is back-to-back connected to a single-phase converter. The three-phase converter absorbs active power from grid at fundamental frequency and controls the dc voltage of capacitor between this converter and single-phase one. The shunt control structure block diagram is shown in Fig. 7.

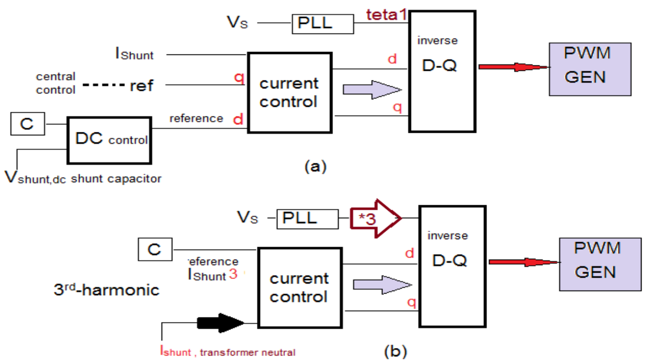

Fig. 7. The shunt control configuration: (a) for fundamental frequency (b) for third-harmonic frequency.

IV. PROPOSED MC-DPFC

The Multi connected Distributed Power Flow Controller (MC-DPFC) is comprised of a number of SSSCs with the common link at their DC sides. The MC-DPFC provides series compensation for multiple lines. This compensation can be both active and reactive. The reactive power required for the series compensation is generated by the series converter itself and the required active power is exchanged from other converters.

Similar to the DPFC, the MC-DPFC consists of multiple single- phase series converters, which are independent from each other. As the MC-DPFC is a power flow control solution for multiple transmission lines, the series converters are installed in different lines. The MC-DPFC can also include shunt converters, but these are not compulsory. The single line diagram of a MC-DPFC is shown in figure 8.

V. MC-DPFC OPERATING PRINCIPLE

In the same way as with the DPFC, the MC-DPFC utilizes the 3rd harmonic current to exchange active power between converters. The operating principle of the DIPFC can be distinguished in two cases: with and without the shunt converter.

A. *With shunt converter*

If the MC-DPFC contains a shunt converter, the shunt converter will supply the required active power for all series converters. Accordingly, each series converter has the capability of injecting both active and reactive power into the transmission line. In this case, the MC-DPFC acts like multiple DPFCs that are installed in different transmission lines. The line with the series converters can be fully controlled to adjust the line impedance, the transmission angle and the bus voltage magnitude. As the MC-DPFC with a shunt converter is identical to a DPFC, that has already been examined, it will not be discussed here.

B. *Without shunt converter*

In a MC-DPFC without a shunt converter, the series converters in different lines will exchange active power with each other. The sum of the active power that is injected by all series converters is zero at the fundamental frequency. It is assumed that the converters in one (or more) of the lines inject both active and reactive power and they are referred to as 'master converters'. Neglecting losses, the active power required by these master converters is supplied by converters in other lines, which can be referred to as 'slave converters'. The master converters can generate a 360◦ rotatable voltage. However, the slave converters can only provide controlled reactive power to the line, because the active power injection of the slave converters depends on the requirement from the master converters and does not have control freedom. In this section, the MC-DPFC without the shunt converter will be considered.

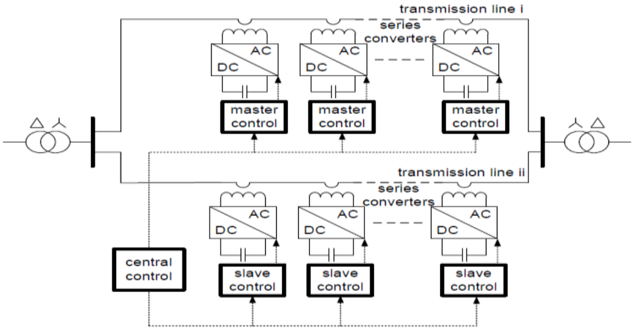

Figure 9 Control the MC-DPFC without a shunt converter

VI. Power Quality Improvement

The whole model of system under study is shown in Fig. 10. The system contains a three-phase source connected to a nonlinear RLC load through parallel transmission lines (Line 1 and Line 2) with the same lengths. The MC-DPFC is placed in transmission line, which the shunt converter is connected to the transmission line 2 in parallel through a Y-Δ three-phase transformer, and series converters is distributed through this line.

VII. Simulation Results

After creating three-phase fault, Fig. 13 depicts the load current swell around 1.1 per unit. The fault time duration is 0.5 seconds. In this case, after implementation of the DPFC, the load current magnitude is comparatively come down. The current swell mitigation for this case can be observed from Fig. 14. The load voltage harmonic analysis, using fast fourier transform (FFT) of power GUI window by *simulink*, as shown in Fig. 16. It can be seen, after DPFC implementation in system, the odd harmonics are reduced within acceptable limits and total harmonic distortion (THD) of load voltage is minimized.

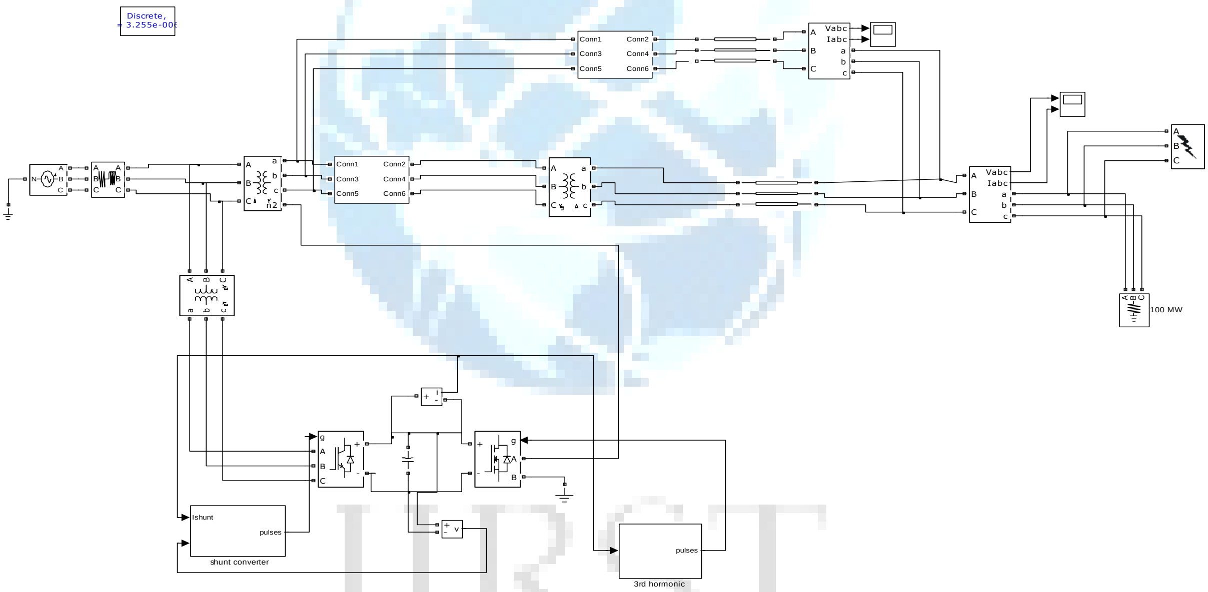

Fig. 10. Simulated model of the DPFC

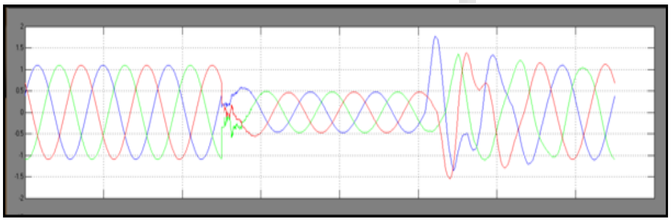

Fig. 11. Three-phase load voltage sag waveform.

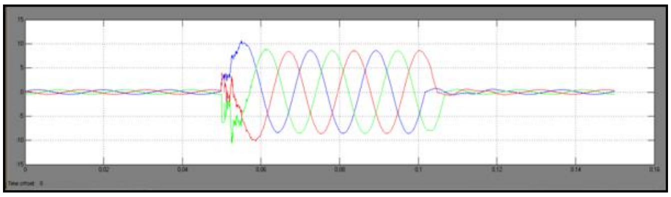

Fig. 13. Three-phase load current swell waveform.

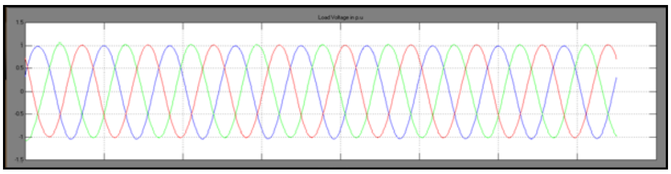

Fig. 12. Mitigation of three-phase load voltage sag with DPFC.

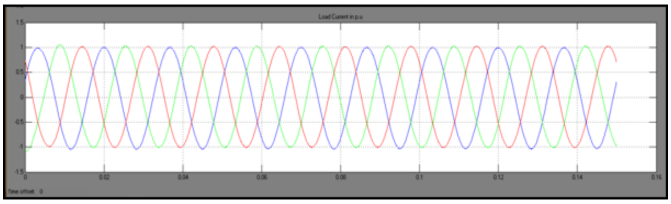

Fig. 14. Mitigation of load current swell with DPFC.

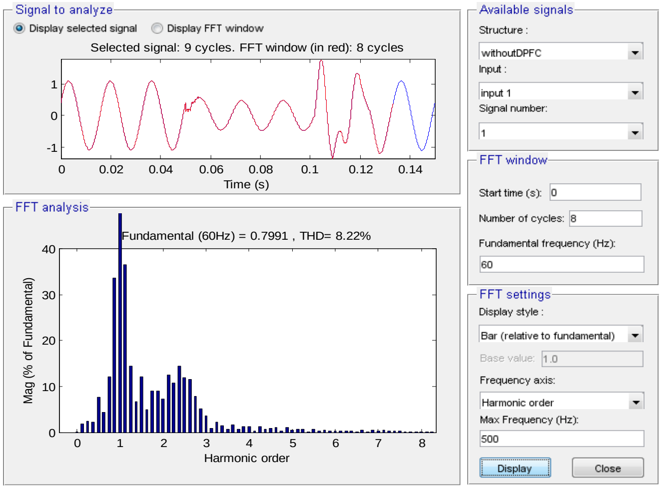

Fig. 15. The load voltage THD.

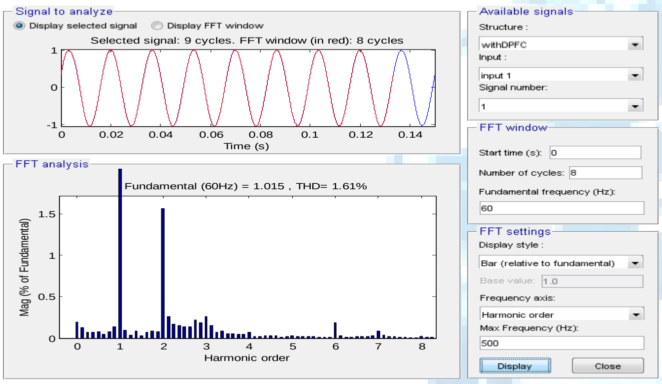

Fig. 16. The load voltage THD.

CONCLUSION

The power quality enhancement of the power transmission systems is an vital issue in power industry. In this study, the application of DPFC as a new FACTS device, in the voltage sag and swell mitigation of a system composed of a three-phase source connected to a non-linear load through the parallel transmission lines is simulated in Matlab/Simulink environment. The voltage dip is analyzed by implementing a three-phase fault close to the system load. To detect the voltage sags and determine the three single phase reference voltages of DPFC, the SRF method is used as a detection and determination method. The obtained simulation results show the effectiveness of DPFC in power quality enhancement, especially in sag and swell mitigation.

TABLE I :

SIMULATED SYSTEM PARAMETERS

Parameters	Values
Rated Voltage	230kV
Frequency	60 Hz
Rated Power	50 MW
Short Circuit Capacity	8500MW
Transmission line length	180 km
Resistance/km in p.u	0.012 Ω
Inductance/km in p.u	0.9337 mH
Capacitance/km in p.u	12.74 µF

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